Emergence of the Green's Functions from Noise and Passive Acoustic Remote Sensing of Ocean Dynamics

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LONG-TERM GOALS

- To evaluate feasibility and determine physical limits of performance of a passive acoustic system for characterization of a time-varying ocean where ambient acoustic noise is utilized as a probing signal.
- To develop a passive remote sensing technique for acoustic characterization of oceanic currents.

OBJECTIVES

1. To demonstrate theoretically emergence of the deterministic Green's functions (GFs) from noise sources distributed in a volume and on boundaries in inhomogeneous, fluid-solid environments with dissipation.
2. To investigate a relation between the deterministic GFs and a two-point correlation function of noise in a low-frequency regime where stationary-point arguments become inapplicable.
3. To quantify degradation of performance of passive remote sensing techniques due to ocean surface motion and other variations of underwater sound propagation conditions in time.
4. To retrieve flow-induced non-reciprocity of acoustic phase and amplitude of the deterministic GFs from cross-correlation of diffuse sound fields generated as a result of scattering by inhomogeneities in the water column and/or by seafloor and sea surface roughness.
5. To determine accuracy of current velocity measurements using acoustic travel time non-reciprocity retrieved from a two-point noise cross-correlation.
6. To evaluate, for shallow- and deep-water scenarios, optimal parameters of a passive acoustic system for ocean temperature and current velocity measurements using cross-correlation of ambient noise and/or sound fields generated by sources of opportunity.

APPROACH

This work includes theoretical research and numerical simulations of ambient noise fields. Theoretical predictions are being verified using low-frequency noise records from the North Pacific Acoustic

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14. ABSTRACT
To evaluate feasibility and determine physical limits of performance of a passive acoustic system for characterization of a time-varying ocean where ambient acoustic noise is utilized as a probing signal.

15. SUBJECT TERMS

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Laboratory (NPAL) array (Worcester and Spindel, 2005; Baggeroer et al., 2005). Experimental data have been kindly provided by Dr. P. F. Worcester and the NPAL Group (J. A. Colosi, B. D. Cornuelle, B. D. Dushaw, M. A. Dzieciuch, B. M. Howe, J. A. Mercer, W. H. Munk, R. C. Spindel, and P. F. Worcester). Our theoretical approach is based on the flow reversal theorem (Godin, 1997), which is an extension of the reciprocity principle to moving media. The approach proved to be instrumental in deriving exact representations of the noise fields and their statistics in arbitrarily inhomogeneous, moving media in terms of deterministic GFs (Godin, 2006, 2007). Moreover, the flow reversal theorem leads to important identities (often termed Ward identities), which relate surface integrals of certain products of GFs to the GF value at a point and underlie an exact, local relation between diffuse noise cross-correlations and deterministic GFs (Godin, 2006, 2007).

Assessment of feasibility of passive acoustic remote sensing requires calculation of averages over finite time interval, rather than statistical ensemble averages. In addition, the fourth statistical moments of the random field as well as their estimates obtained with averaging over a finite time interval need to be calculated. Again, the integral representations of the noise field due to random sources distributed on a surface and/or in a volume, which are obtained from the flow reversal theorem, are the starting point of the analysis. Unlike the second statistical moments (Rytov, 1953; Godin, 2007), closed-form, exact relations for the fourth moments and finite-time averages are unlikely to exist in generic inhomogeneous media. When applicable, asymptotic techniques (Snieder, 2004; Godin, 2006) are employed to evaluate the higher statistical moments and the finite-time averages. Specific features of the oceanic environment, such as slowness of the variation in the horizontal plane compared to variation with depth, are utilized in conjunction with the parabolic approximation and/or normal mode representation of the field to determine the information content of two-point cross-correlations of the ambient noise and of the multiply-scattered field from sources of opportunity. Quasi-stationary approximation (Godin, 2002) is used to quantify effects of the sea surface and the sound speed time-dependences on feasibility of inverting noise cross-correlations for parameters of the sound speed and, especially, current velocity fields.

The key individuals that have been involved in this work are Oleg A. Godin (CIRES/Univ. of Colorado and NOAA/ESRL) and Nikolay A. Zabotin (CIRES/Univ. of Colorado). Dr. Zabotin focused on evaluation of observation times necessary for GF retrieval from diffuse noise fields in an underwater acoustic waveguide and on experimental data processing. Dr. Godin took the lead in theoretical description of long-range correlations of random acoustic fields in inhomogeneous, moving or motionless media.

WORK COMPLETED

Two-point correlation functions of sufficiently diffuse wave fields generated by uncorrelated random sources are known to approximate deterministic Green's functions between the two points. This property is utilized increasingly for passive imaging and remote sensing of the environment. We have shown that the relation between the Green's functions and the noise cross-correlation function holds under much less restrictive conditions than previously thought, namely, when ambient noise sources have finite linear dimensions which can be large compared to the wavelength (Godin, 2009f).

Using the method of a stationary phase, the information content of the cross-correlation function of non-diffuse noise has been investigated (Godin, 2009d, g), and the accuracy of passive measurements

of the acoustic travel times, path-averaged sound speeds and current velocities has been evaluated (Godin, 2009g).

Retrieval of environmental parameters from time-averages of noise cross-correlations requires sufficient exposure times. The exposure times have been estimated assuming that the noise sources are located either on a curve or on a surface. Earlier estimates of the necessary averaging time have been extended to account for arbitrary power spectra of noise and for noise field anisotropy (Zabotin and Godin, 2009).

Cross-correlation functions of thermal noise have been calculated and related to deterministic Green's functions, vectors, and tensors in flow-structure problems, where the condition of thermal equilibrium does not necessary hold. Relations have been established between the type of the fluctuating physical variable being measured (acoustic pressure in the fluid, fluid-solid boundary displacement, stresses in the solid, etc.) and the type of the Green's function (vector, tensor) being retrieved from noise correlations (Godin, 2009a).

For further use in analyses of diffuse noise fields and their possible utilization in passive acoustic characterization of various aspects of the underwater environment, acoustic GFs have been studied for various scenarios of interest. In particular, our earlier finding that travel times of ray arrivals may remain stable and predictable when trajectories of individual rays are strongly distorted and unpredictable due to multiple scattering of the wave by sound speed fluctuations, has been extended to arbitrary acoustically anisotropic environments (Godin, 2009e), such as an ocean perturbed by internal gravity waves with their attendant flow velocity and sound speed variations. Application of acoustic energy streamlines for description of wave propagation and diffraction has been analyzed, and a simple law governing refraction of energy streamlines at an arbitrary interface of two fluids has been obtained (Godin, 2009b, c).

Theoretical methods of investigation of underwater sound fields in range-dependent and horizontally inhomogeneous media with and without currents have been summarized in a book (Brekhovskikh and Godin, 2009).

RESULTS

We have demonstrated that all theoretical results previously established for the two-point correlation function of high-frequency wave fields due to delta-correlated sources remain valid for long-range cross-correlation of wave fields due to extended random sources as long as the correlation length of the latter is small compared to the size of the Fresnel zone at wave propagation between the two points (Godin, 2009f). Consequently, the cross-correlation function of ambient noise generated by extended random sound sources in moving fluids or fluid-solid systems, as in the case of delta-correlated sources, approximates the sum of the GFs, which describe wave propagation in opposite directions between the two points..

We established that, unlike the amplitude information contained in the deterministic GF, the phase information or the travel times between receiver locations along various eigenrays can be retrieved from the noise cross-correlation function without any detailed knowledge about properties or locations of the noise sources. Passive measurements of the travel times require that the random source density

varies gradually in space or, equivalently, noise directivity in each point is a gradual function of direction (Godin, 2009d, g).

We have quantified errors in the eikonal estimates retrieved from the noise cross-correlation function. These errors stem from non-uniformity of the random sources distribution or, in other words, from the noise field not being perfectly diffuse (Godin, 2009g). Our results refer to the eikonal estimates, which are obtained with sufficiently large noise averaging time. Additional errors may occur when the averaging time is not sufficient to ensure that time averages approximate statistical mean values.

Measurements of acoustic noise performed during the 1998-1999 Billboard Array Experiment (Baggeroer et al., 2005) have been re-examined with the goal of extracting environmental information. The data was obtained by the NPAL group and have been made available for this study by Dr. P. F. Worcester. Two-point noise cross-correlation function has been evaluated by averaging time series of noise recorded on various vertical line arrays (VLAs) that comprise the Billboard Array. For any two hydrophones, the cross-correlation function has been found to have a number of robust peaks (Fig. 1). Statistical distributions of noise have been utilized to differentiate between the peaks of different origin and to identify those peaks, which can be used to retrieve information about the sound speed without detailed knowledge of the noise sources.

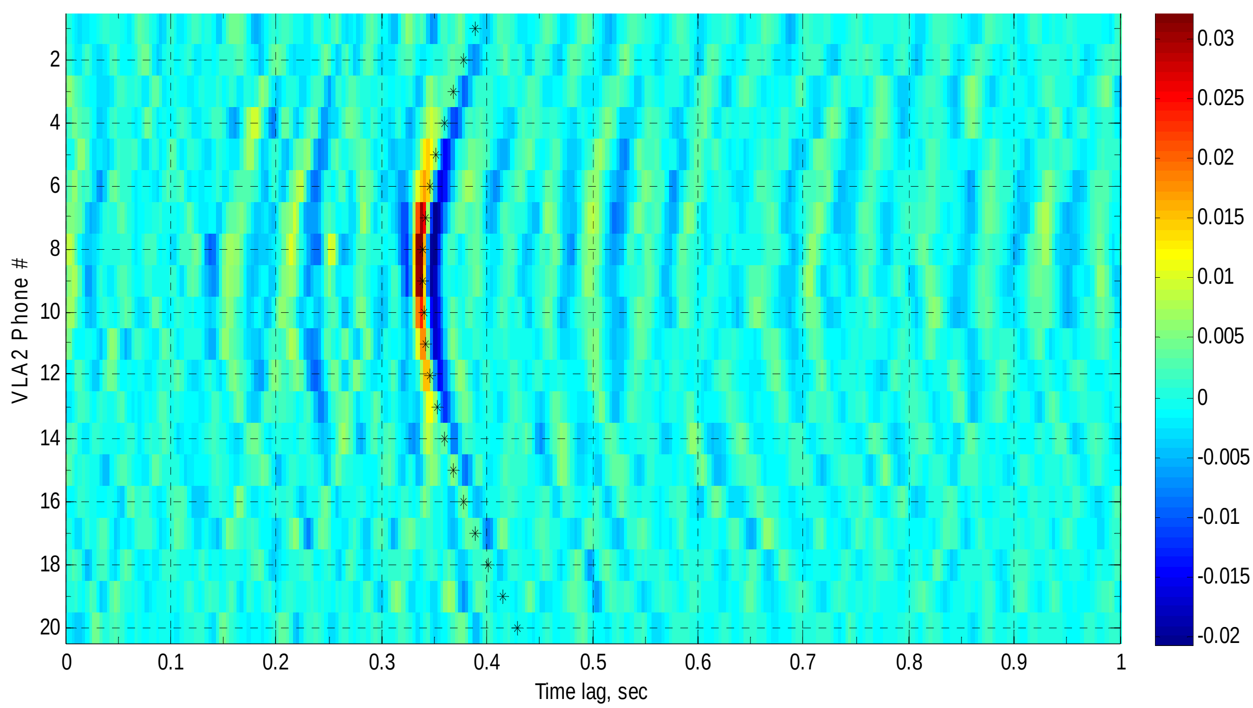

Figure 1. Cross-correlation function of the ambient noise recorded by the hydrophone #9 of the VLA1 and twenty hydrophones of the VLA2 of the NPAL Billboard Array. Stars show travel times calculated using a nominal sound speed profile.
[The noise cross-correlation function is shown as a function of time delay ranging from 0 to 1 sec and depth expressed in terms of the hydrophone number. The cross-correlation function takes values between -0.02 and 0.03, with its peaks and troughs bracing the theoretically predicted travel times at most hydrophones. The strongest peaks and troughs are observed for the VLA2 hydrophones located at depths close to the depth of the hydrophone #9 of the VLA1.]

After averaging over a few hours of noise records, the cross-correlation functions exhibit peaks which correspond to travel times of the direct eigenray between the hydrophones, as confirmed by comparison with calculations for a nominal sound speed profile (Fig. 1). The difference between the acoustic travel times measured through the noise cross-correlation and the predicted travel times is attributed to the difference between the nominal and actual sound speed profiles. The travel time differences for various hydrophone pairs have been successfully inverted to retrieve the sound speed field between pairs of VLAs up to the maximum separation of about 4 km between the VLAs that comprise the Billboard Array. In this experiment, accuracy of the inversion is found to be limited by the recording bandwidth and the noise directionality. To our knowledge, this is the first experimental demonstration of the feasibility of passive ocean acoustic tomography in deep water.

IMPACT/APPLICATIONS

Results of experimental data processing confirm theoretical estimates of the averaging time necessary for emergence of deterministic Green's functions from ambient noise in the ocean and validate the concept of passive ocean acoustic tomography. Because of its lower capital costs, ability to provide long time series of data, and a negligible impact on the environment, including marine mammals, passive acoustic tomography may find applications in various ocean observing systems, where the traditional, active tomography is deemed too expensive or too invasive.

RELATED PROJECTS

Passive Radio Imaging for Applications in Water Resource Management, Glaciology, and Space Weather Monitoring, a one-year project funded by CIRES under its Innovative Research Program, see http://cires.colorado.edu/science/pro/irp/2009/. The project utilizes the availability of extensive digital records of radio noise in the HF band to explore the feasibility and possible applications of a radio-wave counterpart of the acoustic noise interferometry.

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